MARS SCIENCE LABORATORY ROVER SYSTEM THERMAL TEST

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Agenda

- Mission Overview
- MSL Spacecraft
- MSL Rover Configuration
- MSL Rover System Thermal Test
  - Test Objectives
  - Test Results
  - Model Correlation
  - Flight Predictions
- Major Conclusions

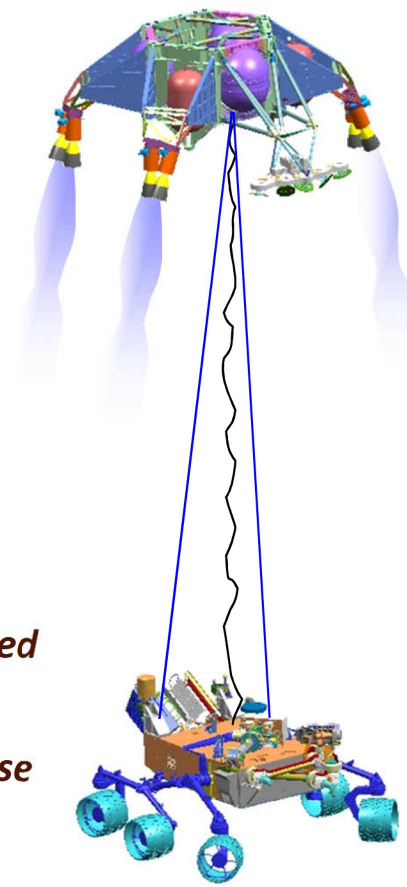
Mission Overview

CRUISE/APPROACH

- *8½-month cruise*
- *Arrive August 5, 2012*

ENTRY, DESCENT, LANDING

- *Guided entry and powered "sky crane" descent*
- *20 ×25-km landing ellipse*
- *Access to landing sites ±30° latitude, <0 km elevation*
- *900-kg rover*

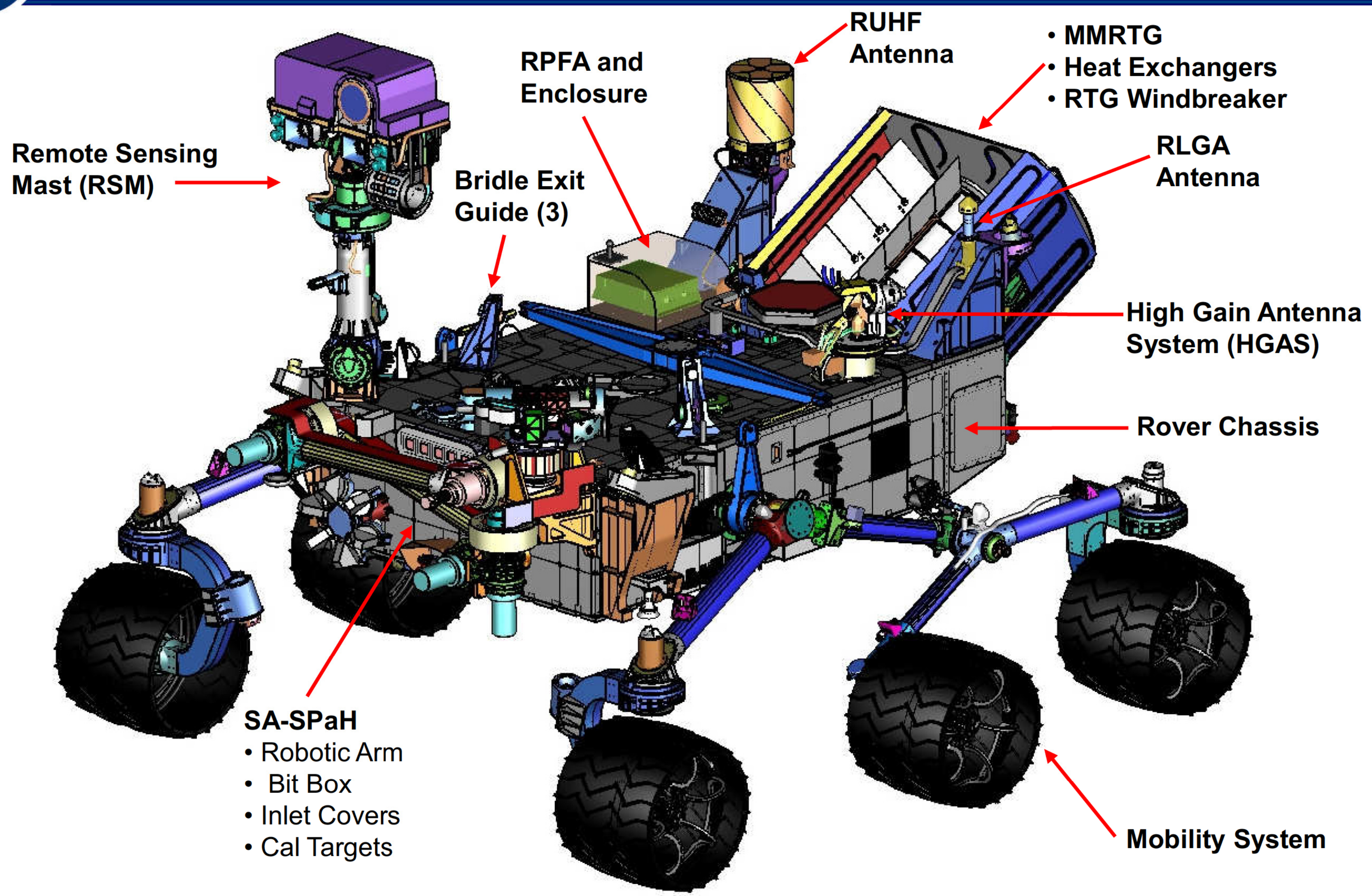


- *Launched Nov. 26, 2011*
- *Atlas V (541)*

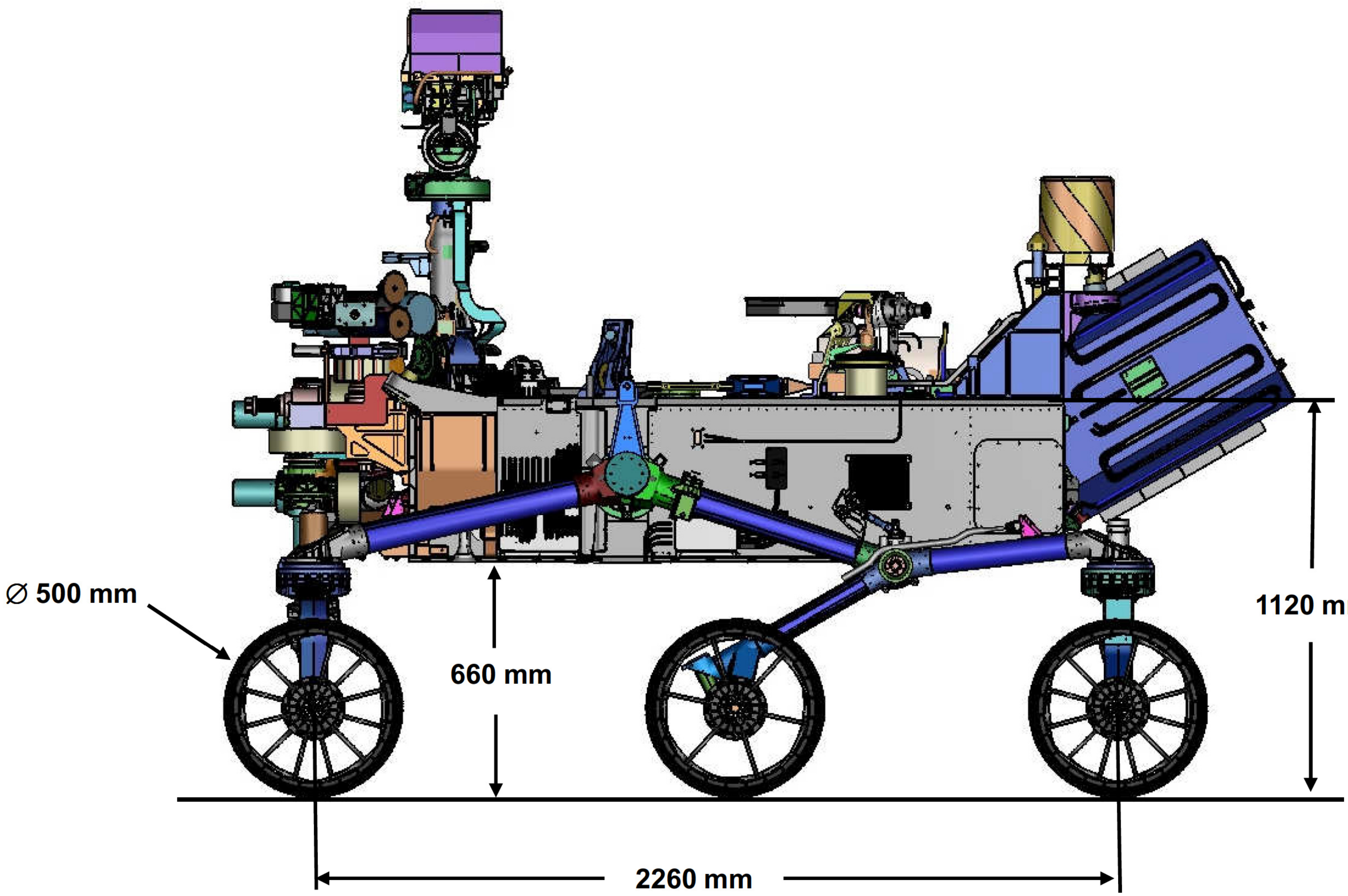
SURFACE MISSION

- *Prime mission is one Mars year (669 Sols)*
- *Latitude-independent and long-lived power source*
- *Ability to drive out of landing ellipse*
- *72 kg of science payload*
- *Direct (uplink) and relayed (downlink) communications*
- *Fast CPU and large data storage*

Rover Traverse Configuration

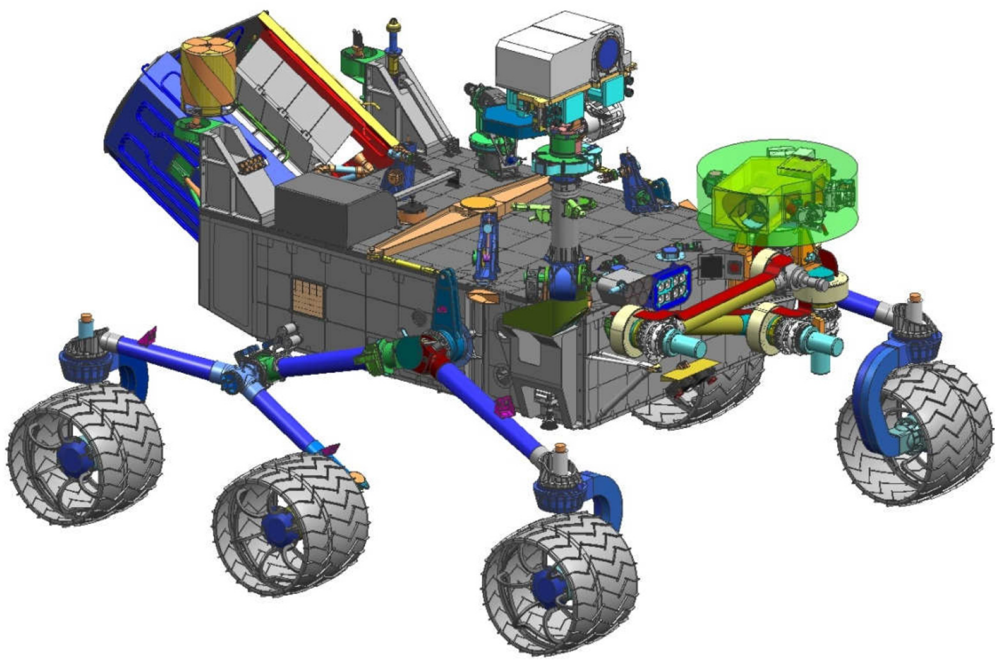


Rover Side View



Test Summary

- The 15-day MSL Rover System Thermal Test was conducted from March 9-24, 2011 in the B-150, 25-ft Space Simulator at JPL.
- All primary test objectives were successfully met.
- The rover thermal design performed extremely well during this test and no violations of Allowable Flight Temperatures were observed.

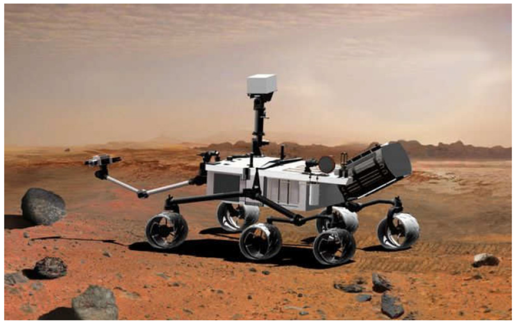


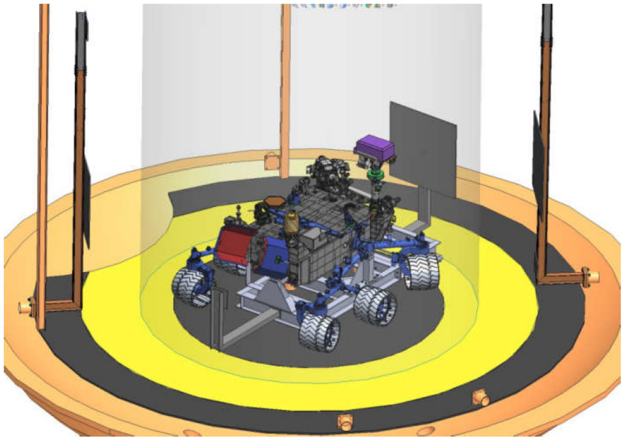
System Thermal Test Objectives Were Met

- Primary Objectives
  - Gather sufficient data from multiple landed environments to permit analytical thermal math model correlation
    - All thermal balance and transient environment cases completed
  - Verify functionality of thermal hardware (heaters, thermostats, PRTs, SLI blanket, rover HRS system)
    - Thermal system performance better than conservative model predicts
  - Verify that the Rover functions properly within specified performance requirements in the simulated Mars surface environment
    - No AFT limit violations during functional tests
  - Extrapolate a correlated analytical model to flight environment to validate Rover thermal design post test
    - Completed
    - Worst-case flight predicts generated for Gale Crater landing site show plenty of temperature margin
      - Hot case RAMP predict = 42C (8C margin to max AFT of 50C)
      - Cold Case RAMP predict = -13C (27C margin to min AFT of -40C)

Why Can't We Validate the Rover Thermal Design in Test?

- This test was **not** a direct validation of the rover surface thermal design. There are many elements of the Mars thermal environment that we cannot simulate inside a thermal chamber on the Earth.
  - Mars acceleration due to gravity is 3/8G,
    - free convection coefficients in the chamber will be higher than those experienced on Mars
  - Chamber backfilled with 10 Torr GN2, not 10 Torr CO2 (Mars atmosphere)
    - GN2 (k = 0.026 W/m*K at 300K)
    - GN2 has a 50% higher thermal conductivity than CO2 (k= 0.017 W/m*K at 300 K)
    - gas conduction and free convection in the chamber will be greater than what is experienced on Mars
  - No dust coverage or degraded thermal paints on the outside of the vehicle
    - white paint properties will be at their BOL values,
  - Solar simulator in the 25 foot chamber will not track (in elevation and azimuth) across the sky and it will not have a diffuse component
  - No wind simulation
  - No independent sky, ground and atmosphere temp control in chamber
    - chamber wall and floor shrouds will be controlled to same temp
    - atmosphere temperatures will be monitored but not controlled



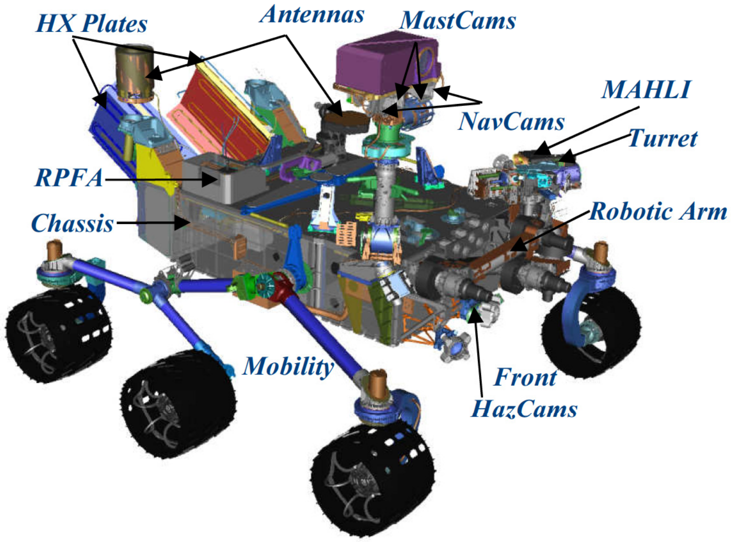


Tests of Design Sensitivity

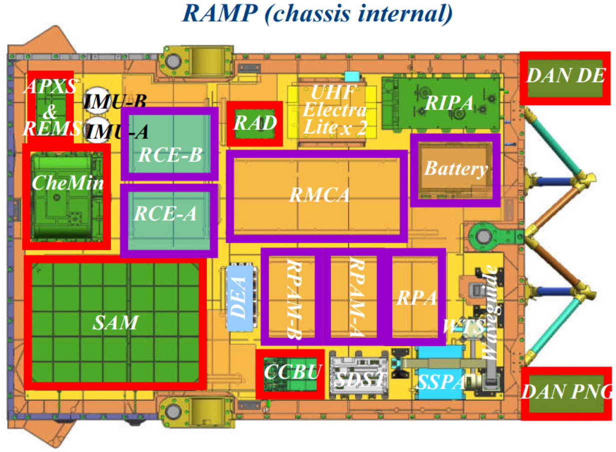
- Effect of GN2 versus vacuum
  - Compare cases #5 (Cold Thermal Balance at -105C) and #7 (Cold Vacuum Test at -105C)
- Effect of RTG Power (Q = 1315 W to 1821 W)
  - Compare case #5 (Cold Thermal Balance at -105C) to case #11B (Functional #5 at -80C)
- Effect of Solar Flux (Q" = 0 W/m^2 to 700 W/m^2)
  - Compare case #10 (Functional Test #4 Env't at -80C) and Case #11A (Hot Thermal Balance at -80C)
- Effect of Shroud Temp (+20C to -105C)
  - Multiple cases

Test Article Description

- Rover consists of the following flight hardware:
  1. All Rover structures, and mechanisms: chassis, RAMP, mobility, actuators
  2. Entire Surface HRS thermal system: RIPA, HX Plates, RAMP
  3. Avionics components: flight computer, power boxes, battery, telecom
  4. All engineering cameras: HazCams, NavCams
  5. Science instruments: MAHLI, MastCams, ChemCam, APXS, REMS, RAD, CheMin, SAM, DAN
  6. Sample Acquisition/Sample Processing and Handling (SA-SPaH) hardware: Robotic Arm, Drill, CHIMRA, 3 Inlet Covers, 2 Contact Sensors, 2 Bit Boxes
  7. RTG simulator



RAMP (chassis internal)



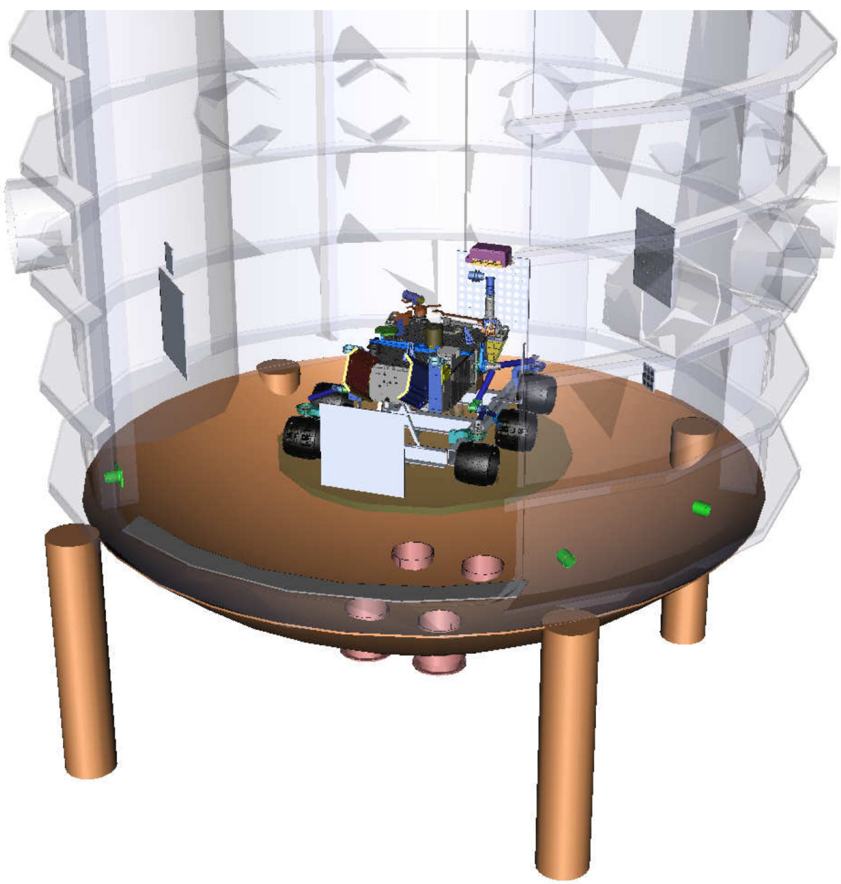
Rover Thermal Hardware

- 58 Flight Heater Circuits Controlled by Rover
  - Custom designed Kapton film heaters from Tayco
  - FSW commandable or mechanical thermostat controlled
  - Primary and secondary heater circuits
- 22 Flight Mechanical Thermostats
  - Internal to RAMP: RBAU (8), CCBU (2), RIPA fault protection (4)
  - External: CCMU (4), RPFA (4)
  - Honeywell TS 700 Series
- 219 Honeywell, 1000-ohm, 2-wire PRTs
  - Data was piped from GDS to TDAS for thermal use
  - Nearby thermocouple measurements used to validate PRT measurements
  - Primary and backup PRTs
- Rover Heat Rejection System (HRS)
  - RAMP, Hot & Cold Plates, RIPAS, bypass valves

Test Instrumentation

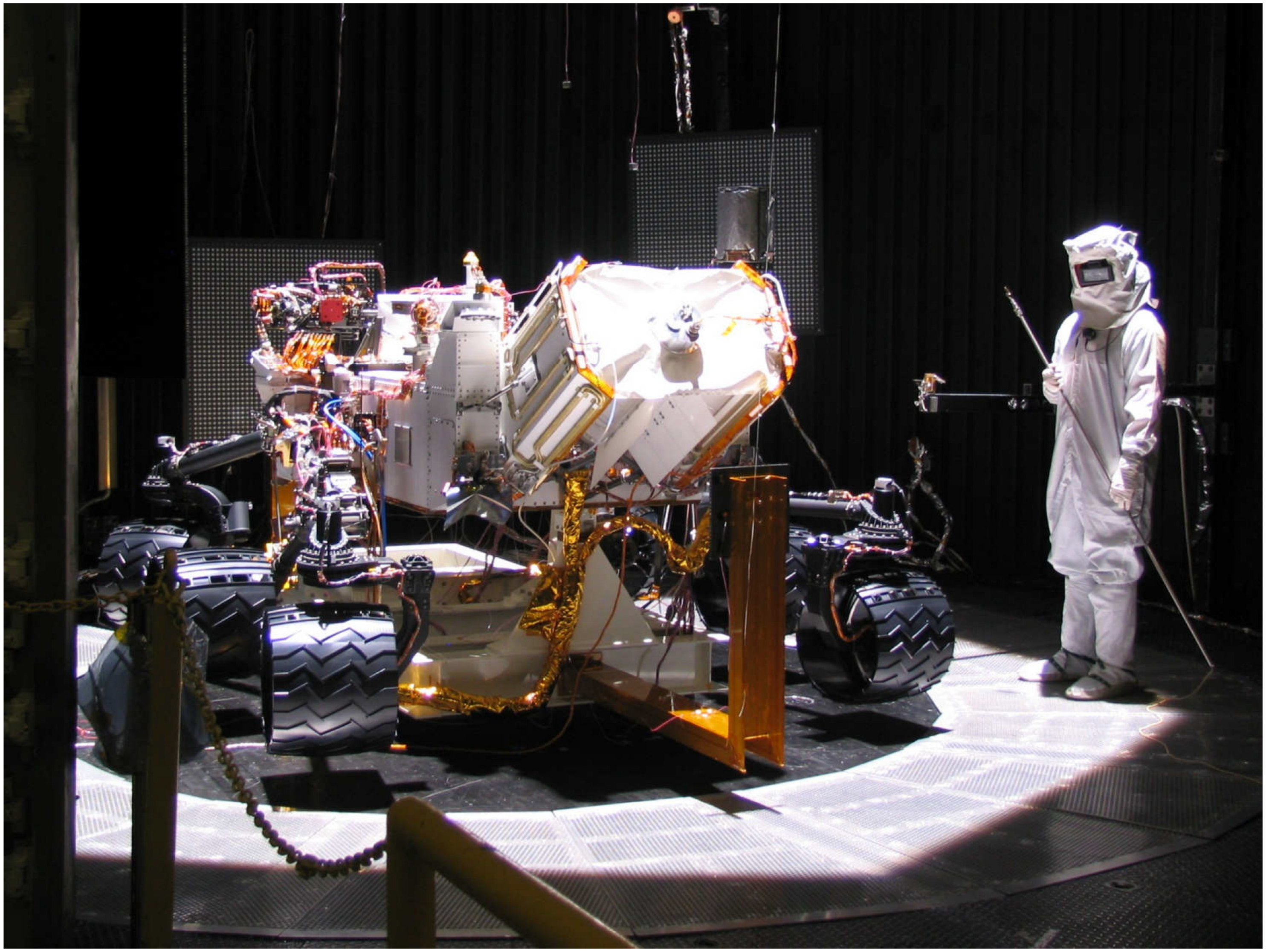
- Thermal Data Acquisition System (TDAS) - LabView
  - 5 TDAS computers (2 for TCs and GSE power supplies, 1 for computed channels, 2 as view-only systems)
  - Scan and record intervals set at 1 minute
  - Connected to UPS & back-up generator
- Heaters powered & controlled by GSE Power Supplies
  - 2 shunt (FLT), 3 CCBU decontamination (FLT), 2 near RAMP too-hot thermostats (TEST)
- 386 Type E, 26-gage Thermocouples
  - 357 on Rover, 11 for chamber atmosphere, 18 on GSE
  - Used for AFT limit and PRT flight sensor verification, near flight thermostat and heater locations, to determine temperature gradient across interfaces, to aid in model correlation
- Additional 150 Thermocouples for Chamber Facility Measurements

Test Setup – Rover in Chamber

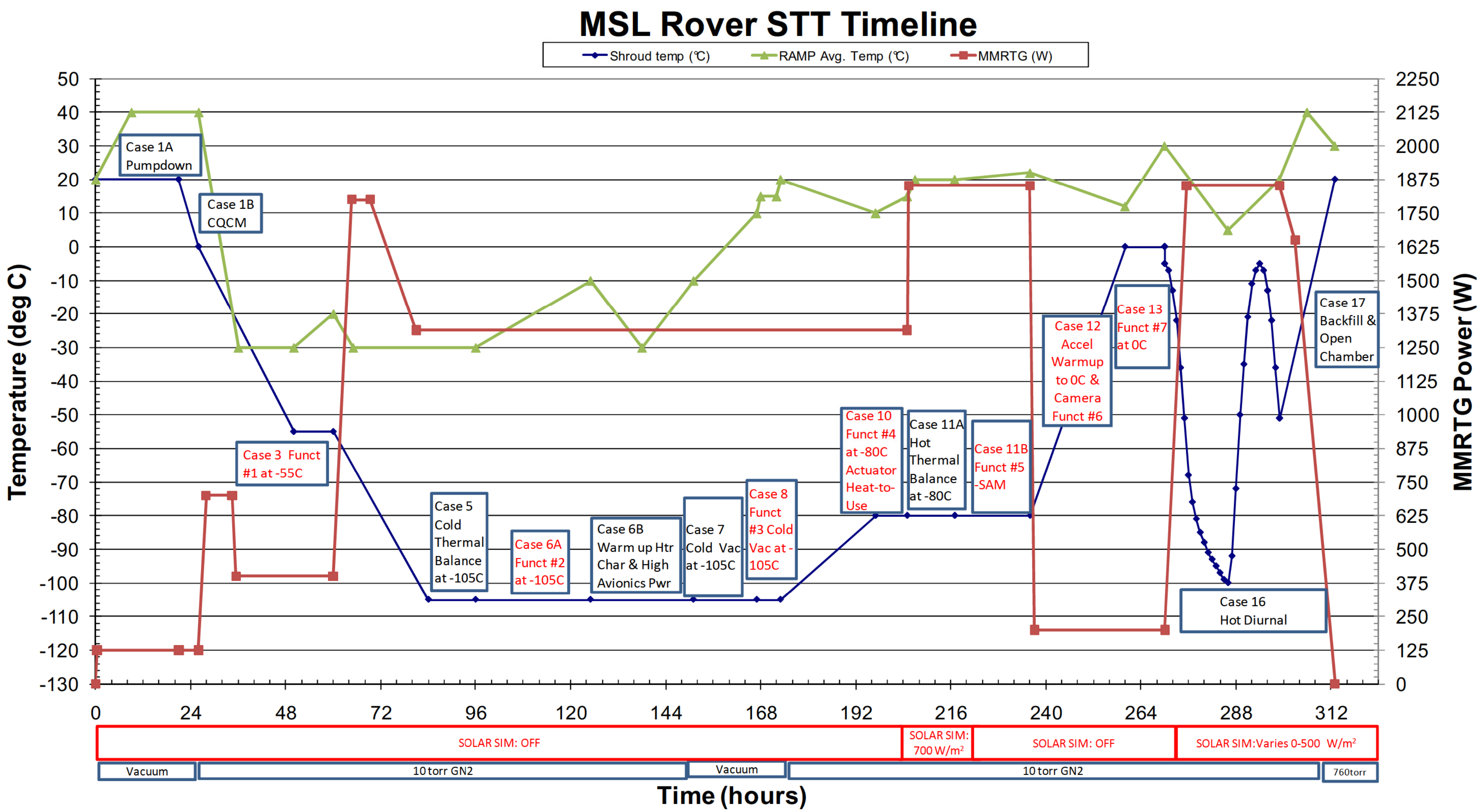


- *Rover Surface Configuration*
- *Mounted on I-beam support frame 6 in. above chamber floor*
- *Powered by Umbilical GSE Power Supply*
- *9 Pyro firings during STT*
  - *HGA, 3x HazCam Covers, RSM, Mobility Bogie Pose, Robotic Arm turret and elbow, Bit Box*
  - *Other pyros fired in B-144 & B-150 prior to chamber installation*
- *Deployments*
  - *Hazcam covers, HGA, RA, RSM*
- *Solar simulator lens created a hexagonal spot – 15 feet, flat to flat*

Surface System Environmental Test



As-Planned STT Thermal Profile Plot



Steady State Thermal Environments

- **Steady State Thermal Balance Cases**
  - **Case 1A** – Pumpdown & Rover Outgas
    - hot case with shrouds at +20C, vacuum environment, low RTG power (500W) and high RAMP power (363W)
  - **Case 5** – Cold Thermal Balance at -105C
    - cold case with shrouds at -105C, moderate RTG power (1315W) and low RAMP power (30W)
  - **Case 7** – Cold Vacuum Test at -105C
    - cold case with shrouds at -105C, moderate RTG power (1315W) and low RAMP power (30W)
  - **Case 11A** – Hot Thermal Balance at -80C
    - Hot case with shrouds at -80C, solar sim on at 700W/m^2, high RTG power (1600W) and high RAMP power (230W)
  - Additional Functional cases that went to steady state due to long duration (Case 3 – Functional #1 went for 23 hours)

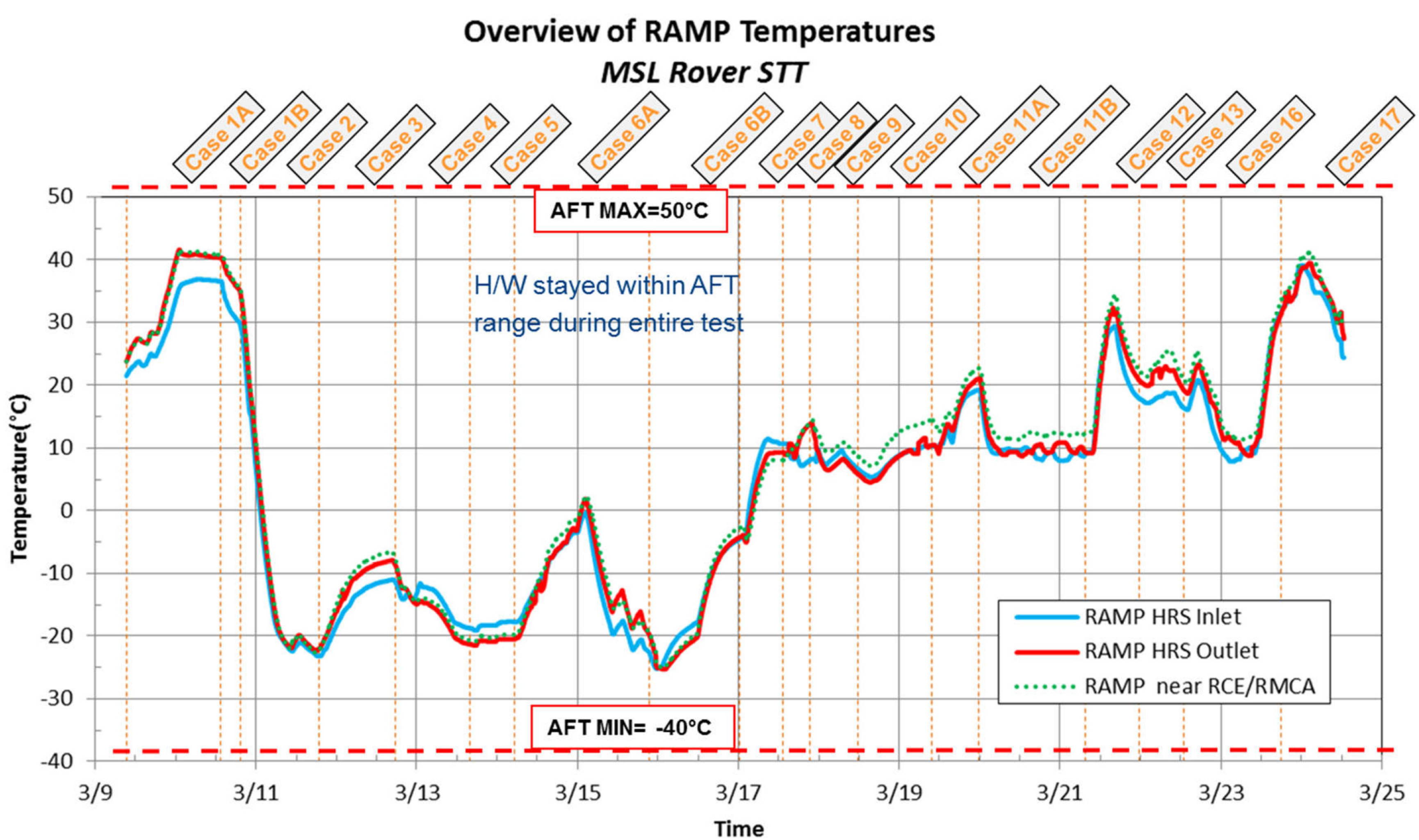
Transient Thermal Environments

- **Transient Cases**:
  - **Case 2** – Accelerated Cooldown to -55C:
    - Global cooldown with shrouds ramping from 0C to -110C
  - **Case 4** – Accelerated Cooldown to -105C:
    - Global cooldown with shrouds ramping from -55C to -125C
  - **Case 6B** – Warmup Htr Thermal Char. & Step Change in RAMP Avionics Power:
    - Actuator & Camera Warmup with shrouds held at -105C; RAMP response to step change in power from 30W to 200W
  - **Case 9** – Accelerated Warmup to -80C:
    - Global warmup with shrouds ramping from -105C to -60C
  - **Case 10** – Actuator & Camera Heat–to-Use:
    - Actuator & camera warmups with shrouds held at -80C
  - **Case 11A** – Hot Thermal Balance –
    - External rover hardware exposure to step change in solar load from 0 W/m^2 to 700 W/m^2
  - **Case 12** – Accelerated Warmup to 0C:
    - Global warmup with shrouds ramping from -80C to +20C

HRS performance in Rover STT

- **In the worst-case cold tested conditions, the RAMP component interfaces were ~3-10 C warmer than predicted**
- **In the hot thermal balance test conditions, the hottest RAMP component interfaces were ~0.2 C cooler than predicted**
- **The temperature difference between HRS fluid inlet & outlet (in RAMP) during test was smaller than predicted**
- **RAMP was very uniform in temperature during STT (~ 2 C gradient in STT vs. ~7 C predicted)**

Overview of RAMP Temperatures



Actuator/Camera Results

- **Actuator and camera warmup heaters have been adequately sized:**
  - Capable of warming up actuators and cameras above AFT in cold environment (-105C shroud, no solar) within expected time duration;
  - Capable of maintaining temperatures with proper duty cycle.

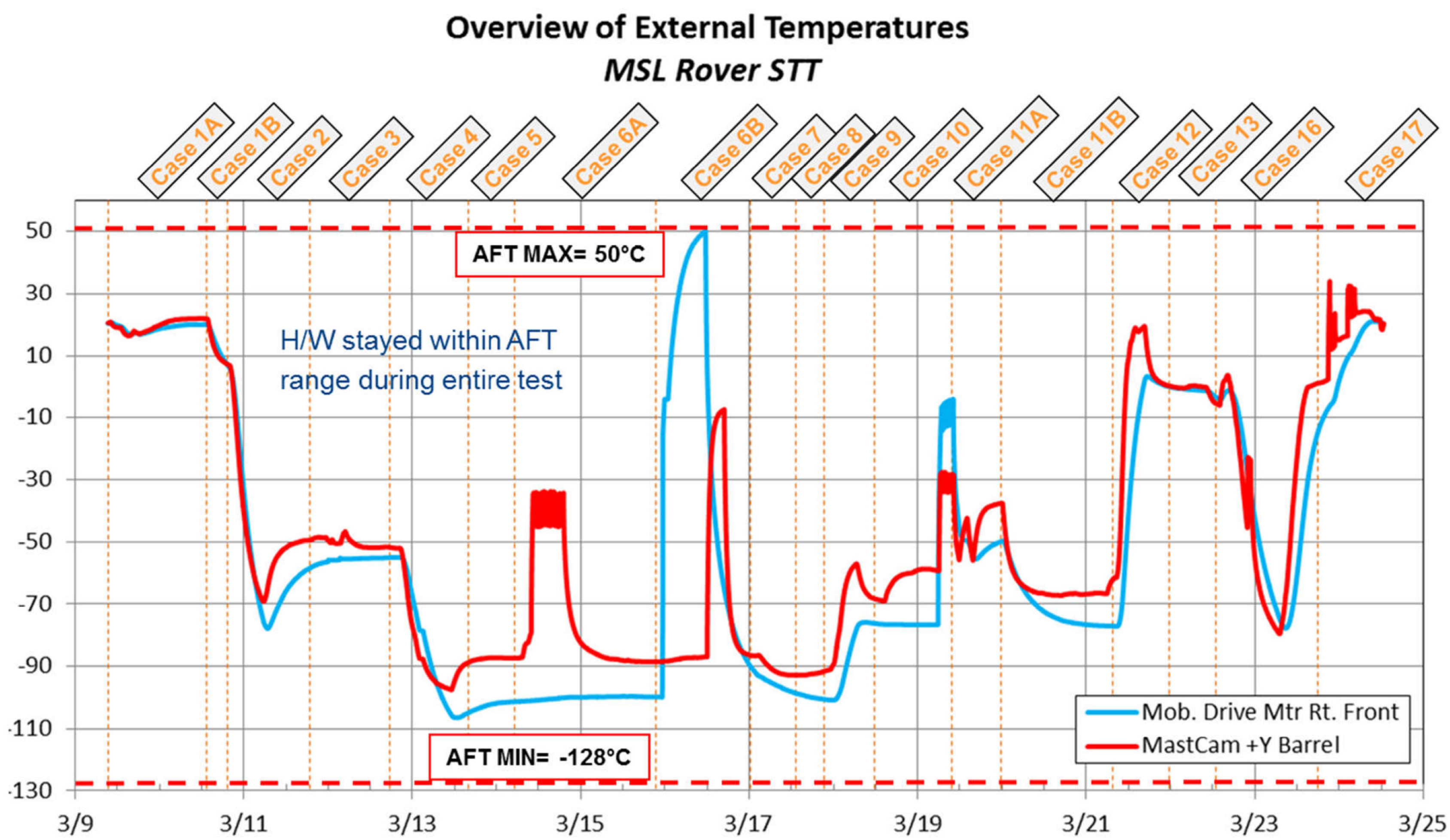
- **Verified Rover's capability to do warmup heater control:**
  - Verified heater switches controlled by both RPAM-A and RPAM-B;
  - Verified FSW heater control in auto mode with selected control PRT's and setpoints;
  - Pre-heat durations were consistent with pre-STT predicts.

- **Actuators and cameras operated within allowable temperatures:**
  - Target temperatures and pre-heat duration followed pre-STT model predicts;
  - Actuators and cameras were warmed up above the min op temperatures (min op Qual, FA, or AFT limits) before the functional (motion or imaging) tests were conducted.

- **Obtained thermal data for thermal model correlation:**
  - Actuators: Mobility, HGA, and Inlet Covers.
  - Cameras: MAHLI and MastCams.

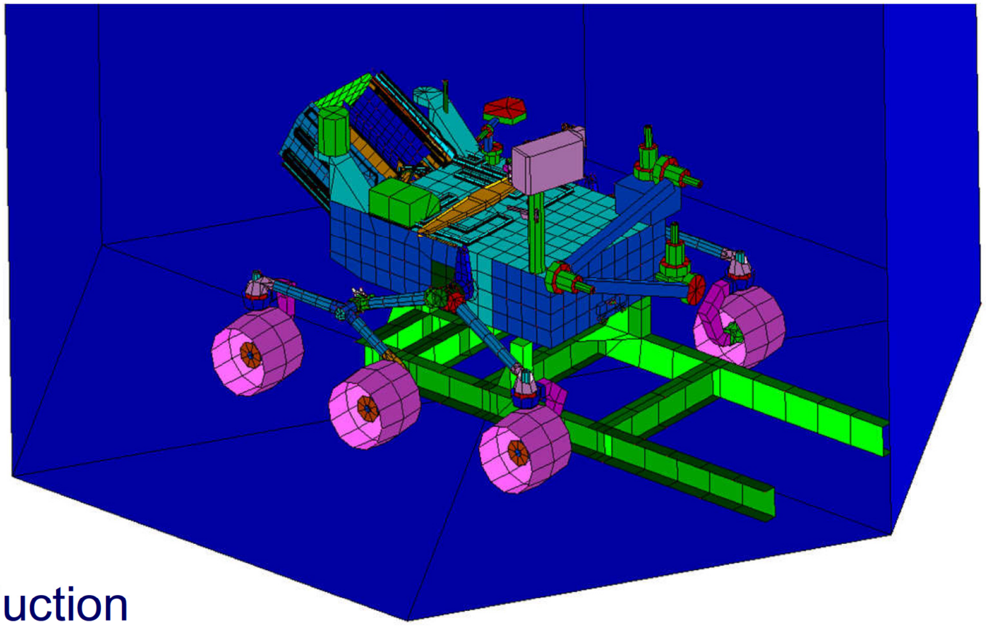
- **Obtained thermal data for checking previously correlated models:**
  - Actuators: RSM, CHIMRA, Drill, and RA.
  - Cameras: HazCams and NavCam (MER).

Overview of External Temperatures



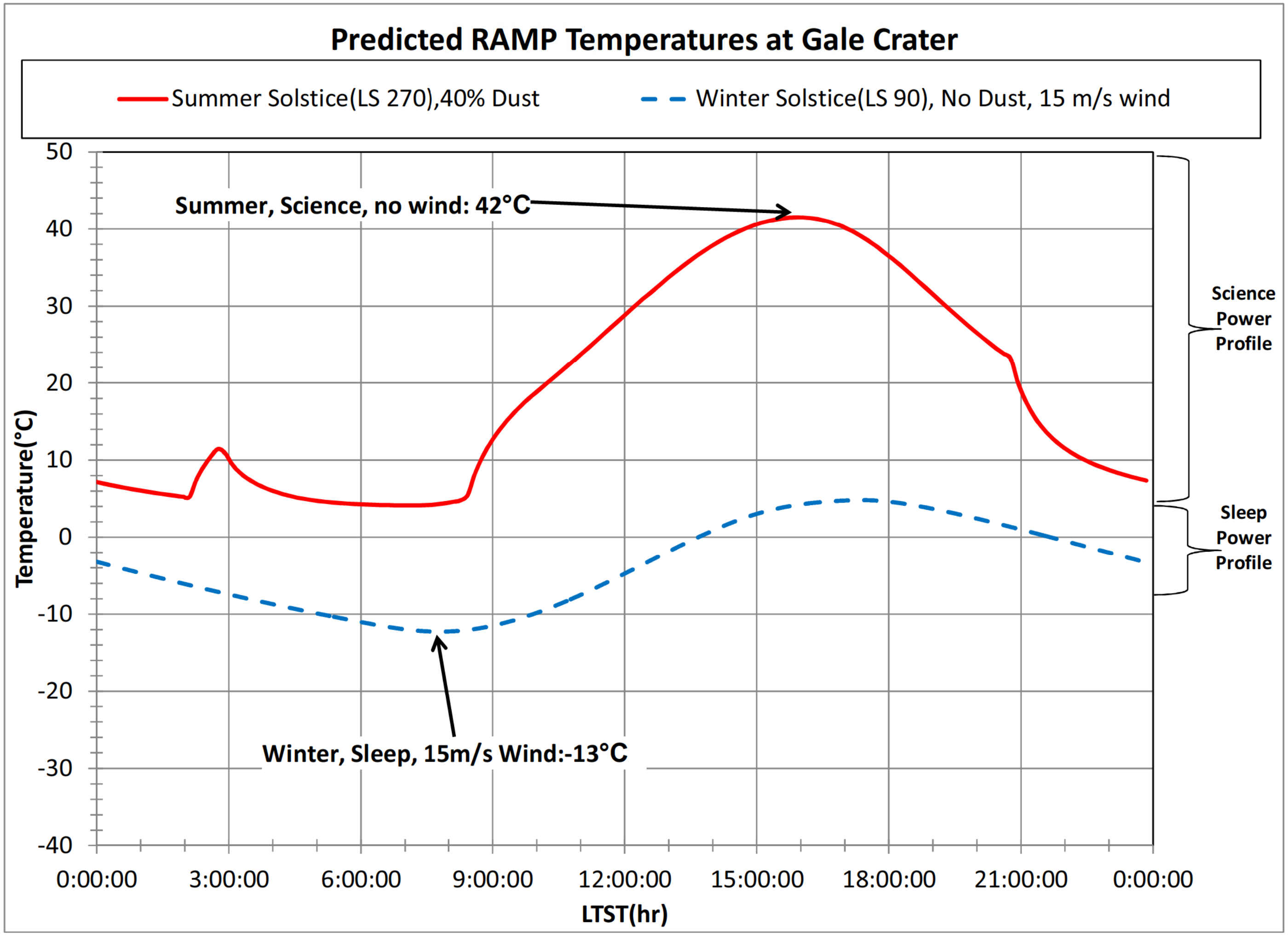
Thermal Model Correlation

- Parameters which were modified to improve rover system-level model correlation with test results included:



- Thermo-optical Properties
  - Emissivity
  - Absorptivity
- Radiation Blockage
- Thermal Conductances
  - Interfaces
  - Cables
  - CO_2 thickness for Gas Conduction
- Convection Coefficients
- Effective Thermal Mass

Flight Predictions



8℃ of margin to Max AFT limit of 50℃

27℃ of margin to Min AFT limit of -40℃

Major Conclusions

- It was a very successful test
- All primary test objectives were met.
- Rover thermal design performed well during this test and no violations of Allowable Flight Temperatures were observed.
- Model correlation work has been done for rover thermal system, actuator & camera thermal models
- Flight predicts have been done
  - Thermal performance predicts for Gale Crater Landing Site (4.5 degrees South latitude) are excellent
- Looking forward to an exciting and successful surface mission – Landing on Aug. 5, 2012, 10:30PM PDT
  Sol 0, 3:03PM LMST in Gale Crater

Acknowledgements

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- ***The authors wish to acknowledge the many engineers and scientists who worked collaboratively on the Mars Science Laboratory System Thermal Test and brought it to a successful conclusion.***

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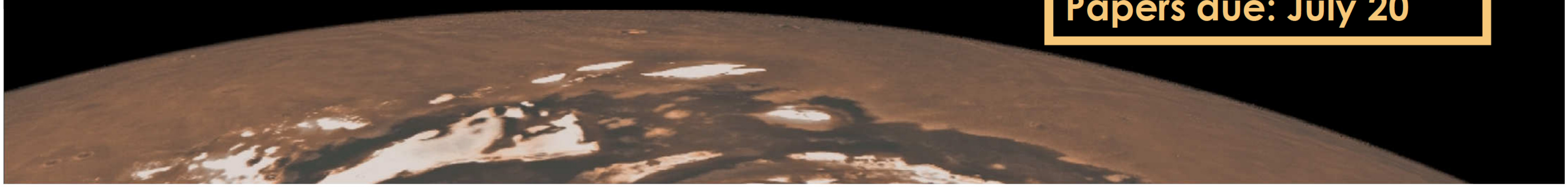


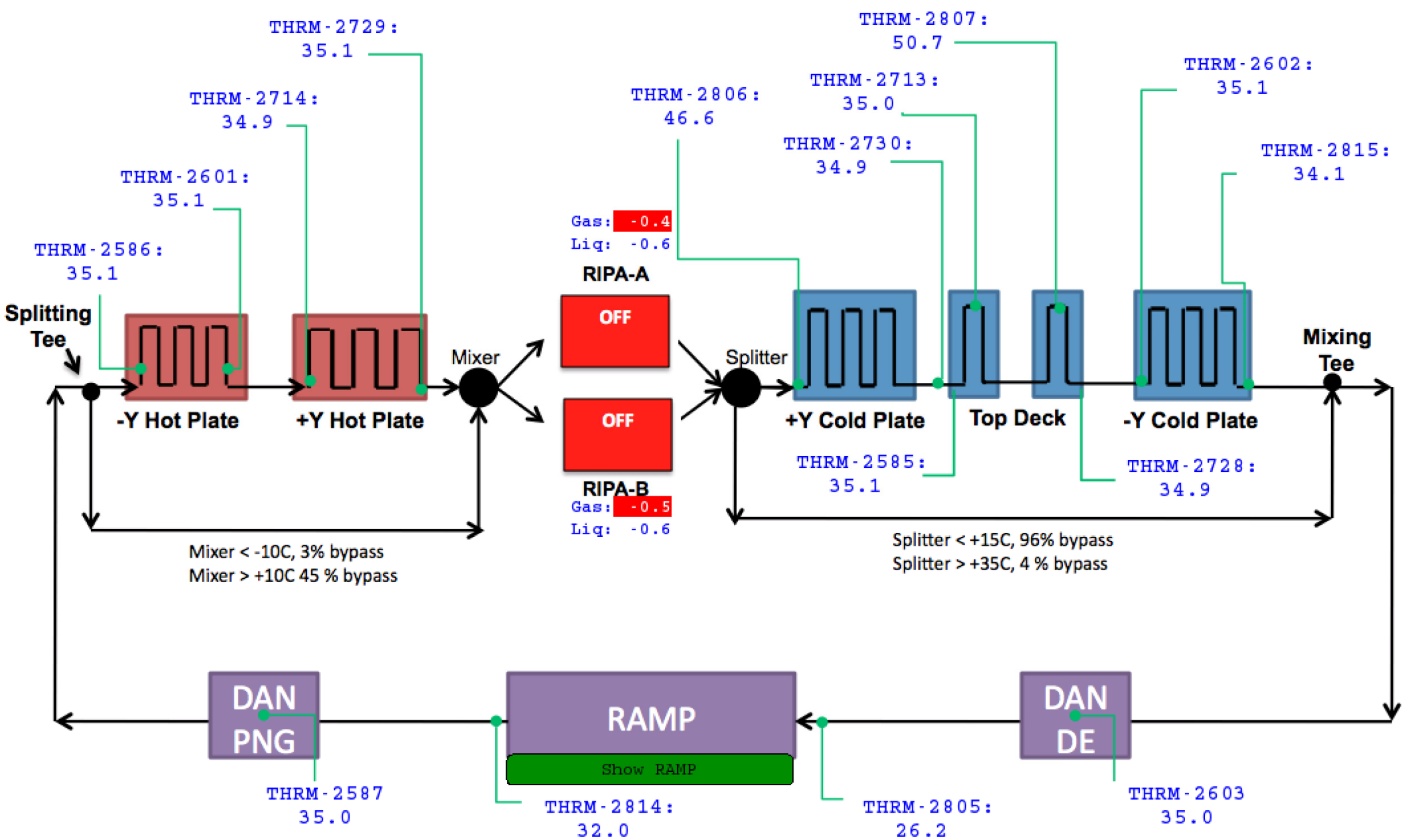
Backup

As-Run Test Timeline

MSL Rover STT Status

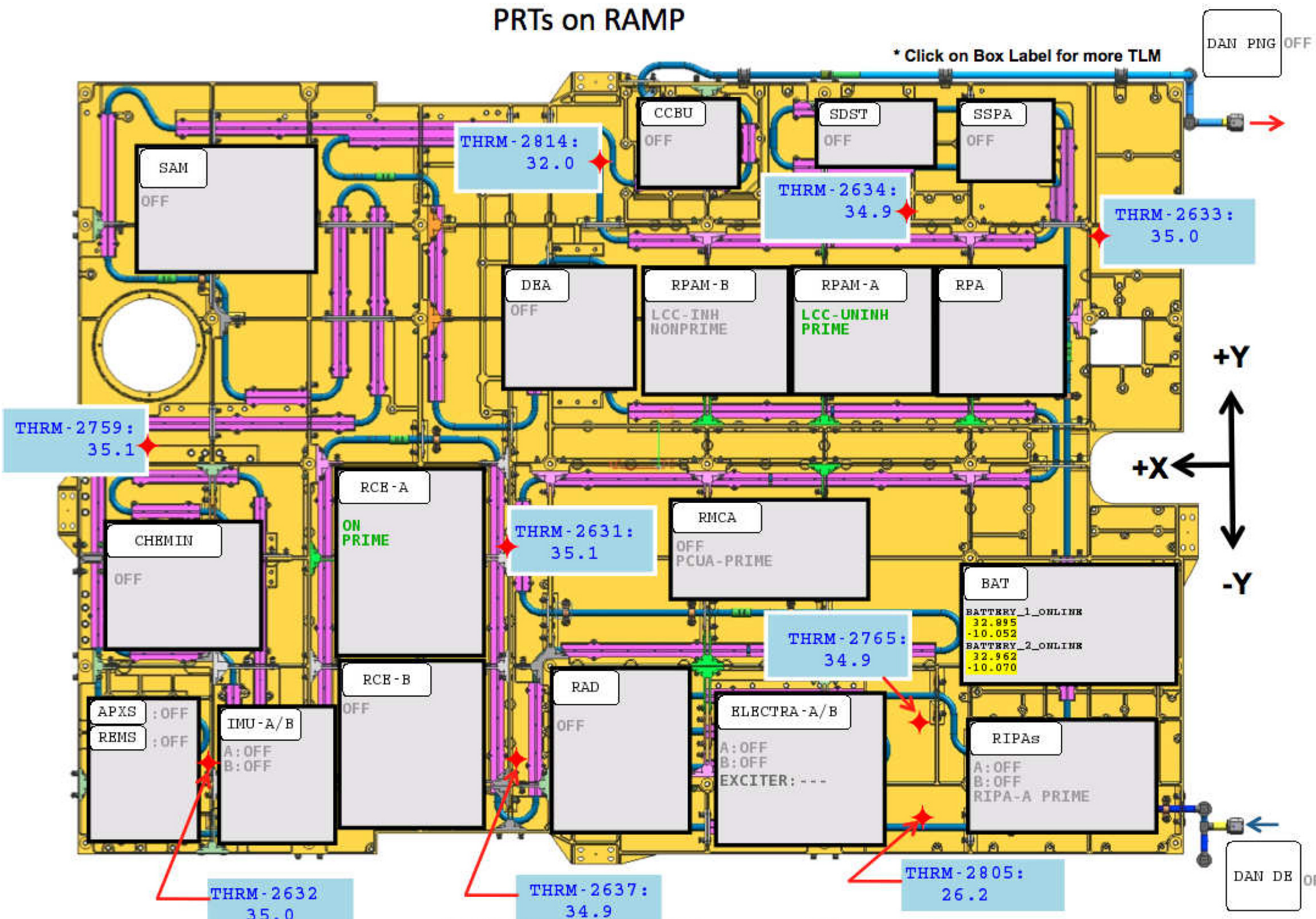
MSL Rover STT	Test Description	Estimated Duration (hrs)	Actual Duration (hrs)	From: *m/d/11 h:mm AM*	To: *m/d/11 h:mm AM*
	Late Start - Planned time was 8:00am	0.0	0.4	3/9/11 8:00 AM	3/9/11 8:23 AM
Test Case 1A	Pumpdown, Rover Outgas & Backup Pump Fault Protection Checkout	21.0	29.1	3/9/11 8:23 AM	3/10/11 1:30 PM
Test Case 1B	CQCM Measurement	5.0	6.0	3/10/11 1:30 PM	3/10/11 7:30 PM
Test Case 2	Accelerated Cooldown to -55C	24.0	23.3	3/10/11 7:30 PM	3/11/11 6:45 PM
Test Case 3	Functional #1: Deployment Verification at -55C	12.0	22.7	3/11/11 6:45 PM	3/12/11 5:30 PM
Test Case 4	Accelerated Cooldown to -105C Environment	24.0	23.5	3/12/11 5:30 PM	3/13/11 5:00 PM
Test Case 5	Cold Thermal Balance at -105C Survival Heater/T'stat Checkout, HGA Warmup Htr Char Test	12.0	13.1	3/13/11 5:00 PM	3/14/11 6:07 AM
Test Case 6A	Functional Test #2 Environment @ -105oC [Cold Case]	29.0	39.2	3/14/11 6:07 AM	3/15/11 9:18 PM
Test Case 6B	Warmup Heater Thermal Characterization & Cold Thermal Balance with High RAMP Avionics Power	26.0	26.7	3/15/11 9:18 PM	3/17/11 12:00 AM
Test Case 7	Cold Vacuum Test at -105C	16.0	13.0	3/17/11 12:00 AM	3/17/11 1:00 PM
Test Case 8	Functional #3 - Cold Vacuum Test at -105C	6.0	8.5	3/17/11 1:00 PM	3/17/11 9:30 PM
Test Case 9	Accelerated Warmup to -80C	24.0	15.0	3/17/11 9:30 PM	3/18/11 12:30 PM
Test Case 10	Functional Test #4: Environment @ -80C Actuator Heat-to-Use & Articulate	8.0	21.5	3/18/11 12:30 PM	3/19/11 10:00 AM
Test Case 11A	Hot Thermal Balance Test at -80C	12.0	13.5	3/19/11 10:00 AM	3/19/11 11:30 PM
Test Case 11B	Functional #5 - SAM on 20C RAMP	19.0	32.0	3/19/11 11:30 PM	3/21/11 7:30 AM
Test Case 12	Accelerated Warmup to 0C & Camera Functional #6 at -40C during Transition	24.0	16.5	3/21/11 7:30 AM	3/22/11 12:00 AM
Test Case 13	Functional Test #7: Environment @ 0oC [Hot Case]	10.0	13.0	3/22/11 12:00 AM	3/22/11 1:00 PM
Test Case 14	*deleted*	0.0	0.0	3/22/11 1:00 PM	3/22/11 1:00 PM
Test Case 15	*deleted*	0.0	0.0	3/22/11 1:00 PM	3/22/11 1:00 PM
Test Case 16	Hot Diurnal Test	29.0	29.0	3/22/11 1:00 PM	3/23/11 6:00 PM
Test Case 16B	*deleted*	0.0	0.0	3/23/11 6:00 PM	3/23/11 6:00 PM
Test Case 17	Backfill and Open Chamber	14.0	17.5	3/23/11 6:00 PM	3/24/11 11:30 AM
	Initial Estimated Total Test Duration (days):	*13.1*	15.1	*:Current Total Test Duration (days)*	
	(hours):	*315.0*	363.5	*: (hours)*	
			-48.5	*Delta in Hours (negative is behind)*	

GDS Fixed Pages



RHRS Loop PRT Overview

GDS Fixed Pages

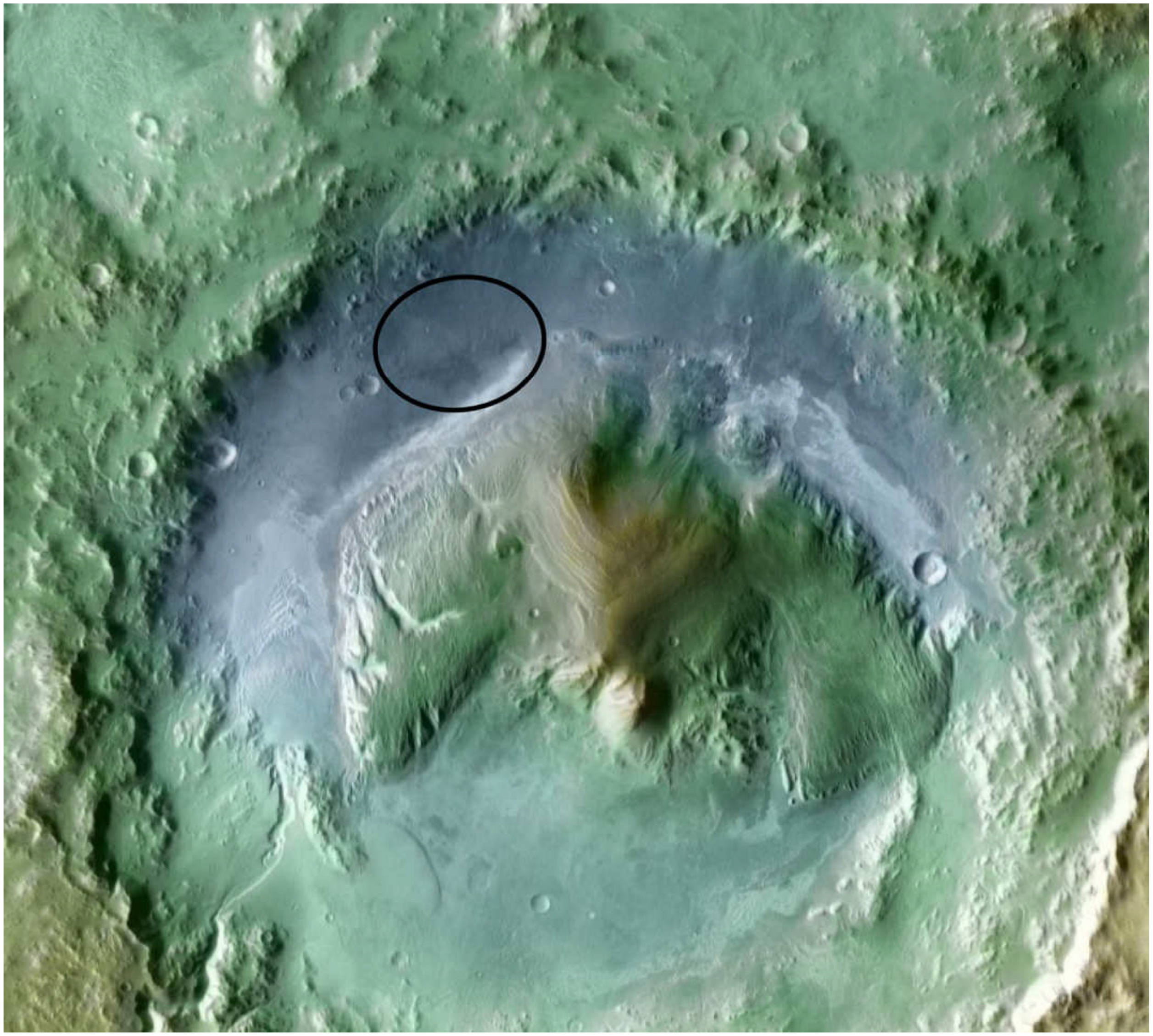


Bird's Eye View of Rover on Mars

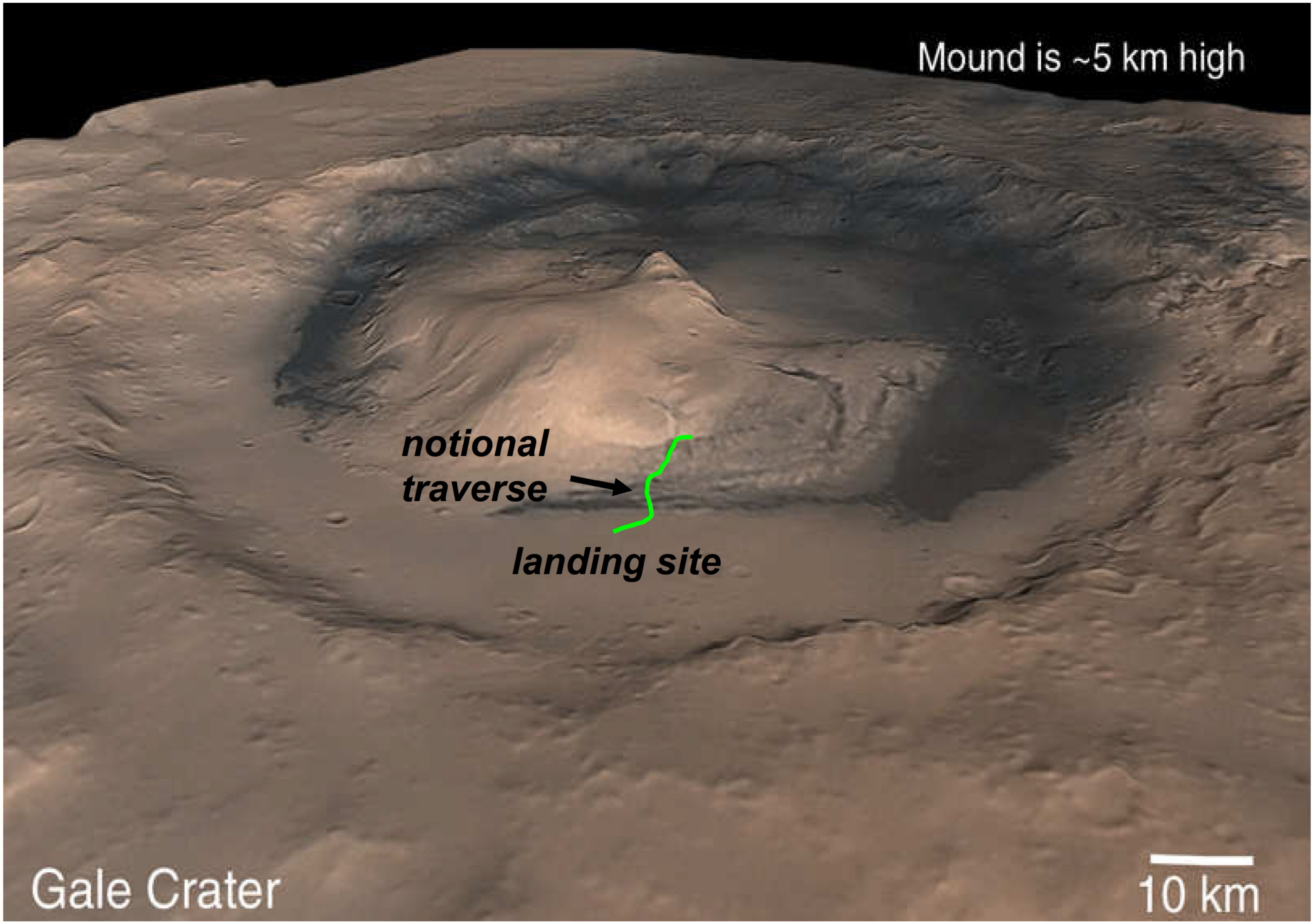
✦ = RAMP PRT location

Gale Crater

Landing Ellipse



Gale Crater


Mound is ~5 km high
notional
traverse
landing site
Gale Crater
10 km

System Test Bed Drills